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National Aeronautics and
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Goddard Space Flight Center
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Abstract

Based on one year of data from the double probe electric field instrument on ISEE-1, a survey of occurrence of micropulsations near and inside the plasmapause has been made. The observed pulsations are classified as Pc 3 and Pi 2. In addition one single event of Pc 1 is observed.

Pc 3 events are common during the local day with a maximum percentage of occurrence as high as 72 in the morning hours. They occur on all frequencies in the Pc 3 band, but the most dominant frequencies are 30-50 mHz (20-33 s. period), and the amplitudes range from 0.1 to 4-5 mV/m peak to peak. The strongest Pc 3 events are nearly linearly polarized. Based on the azimuth angle of the polarization, the orientation is usually either radial from the earth or east-west. The direction of rotation for the electric field vector is most often left handed in the morning sector and right handed in the afternoon sector. The Pi 2 events are concentrated on the local nightside. The amplitude for these pulsations is typically of the order of 2 mV/m peak to peak, but can range as high as 20 mV/m peak to peak. These pulsation events are usually composed of several frequency components, with the dominant frequency most often in the band 10-16 mHz (62-100 s. period).

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Introduction

Ultralow Frequency (ULF) waves of natural occurrence, also known as micropulsations, have been studied extensively for more than two decades (e.g., see review by Campbell (1967), Saito (1969), Jacobs (1970), Orr (1973), Raspopov and Lanzerotti (1976), Nishida (1978)) and a reasonable picture of occurrence distributions has been established based on ground (e.g., Jacobs and Sinno (1960), Saito (1964), Orr and Webb (1975)) and space (Heppner et al. (1970), Arthur et al. (1977), Singer et al. (1979)) observations. Most previous papers have dealt with the magnetic field component of these waves. This paper is, however, based on data from the double probe electric field instrument on the ISEE-1 satellite (Heppner et al. (1978a)). The period range, 10-150 seconds dealt with in this study includes the Pc3 and Pc4 bands as well as parts of the Pi1 and Pi2 bands (Jacobs et al. (1964)). As discussed later we suggest that most of the pulsations included in this survey may be classified as Pc3 (period 10-45) and Pi2 (period 40-150).

ISEE-1 and ISEE-2 were launched into similar orbits on October 22, 1977. Figure 1 shows a projection of the orbit in the equatorial plane, while Table 1 gives some of the major parameters for the ISEE-1 spacecraft and its orbit. The major axis of the orbit elipse drifts approximately 1 degree per day, which brings the orbit back to it's original position after one year. The orbit period is close to 57 hours, of which 1-3 hours are spent inside the plasmapause. The satellite is spin-stabilized with the spin vector maintained perpendicular to the ecliptic plane within ± 1 degree and pointing north.

The electric field instrumentation measures the difference in the ambient plasma potential between the midpoints of the two conducting segments of the antenna shown in the inserted frame of Figure 1. This

differential voltage, from which the spin plane component of the electric field can be calculated by subtracting the induced $\vec{v} \times \vec{B}$-term (where $\vec{v}$ is the velocity of the satellite and $\vec{B}$ is the ambient magnetic field), is sampled 8 or 32 times per second at low and high bit rates, respectively. A more complete description of the double probe electric field instrument on ISEE-1 is given by Heppner et al. (1978a).

Data

Figure 2 shows three samples of the raw data which includes the $\vec{v} \times \vec{B}$ term in addition to the ambient electric field. The $\vec{v} \times \vec{B}$ term becomes the dominent part of the observed field as the satellite approaches the earth where the geomagnetic field ($\vec{B}$) and the velocity ($\vec{v}$) increase. The small vertical arrows in the Figure give the times when the measurement axis is pointing at the sun, which also indicates the direction of the X-axis in solar ecliptic coordinates.

As shown, a wave with period close to 0.5 second and amplitude up to 3-4 mV/m peak to peak is super-imposed on the spin modulated data. This inbound pass through the plasmasphere (close to noon local time on December 11, 1977), is the only pass where we so far have detected pulsations in the Pc1 period range (0.2-5s). As the goal of the present paper is to give a statistical survey of the occurrence of pulsations, we will in the following concentrate on the longer period pulsations which are present in almost every pass.

Using a least squares fit program, the plots shown in Figure 3 and 5 result from one sample of the amplitude and the phase angle (relative to the sun direction) per spin period. The solid and dotted graphs in these Figures give, respectively, the amplitude and the phase angle for the measured electric field, which includes $\vec{v} \times \vec{B}$.

In Figure 3, three typical examples of fairly strong pulsations in the Pc3 period range are shown. Pulsation events in this period range generally show a coherent behavior for more than ten minutes with amplitudes typically ranging from 0.1 mV/m to 4-5 mV/m peak to peak. Figure 4 shows the power spectra for parts of the pulsation events in each panel in Figure 3. The solid lines give the result from a maximum entropy method while the dashed lines result from calculations based on the method described by Blackman and Tukey (1958). The peak at zero mHz is caused by the slope of the $\vec{v} \times \vec{B}$ term. These pulsations occur at all frequencies in the Pc3 band, but most often in the frequency range 30-50 mHz (i.e., period 20-33s). As shown, a single peak strongly dominates the spectrum for these pulsations.

Figure 5 gives three examples of the longer period pulsations and the corresponding power spectra are shown in Figure 6. As can be seen, the pattern is not as regular in either amplitude or phase when compared with the pulsations shown in Figure 3. The amplitude of these pulsations is typically larger and may range as high as 20 mV/m peak to peak. Also the duration of occurrence along a pass is usually shorter than for the Pc3 events. The spectrum of a single event is generally composed of several frequency components (Figure 6, center and right panels), but only one single component is also observed (see Figure 6, left panel). Pil's are often seen as high frequency riders on these pulsations. The dominant frequency component appears most often in the range 10 to 16 mHz (i.e., period 62-100s).

Analysis Procedure

By means of visual scanning, we have examined one year of data from November 1, 1977 to October 31, 1978. During this period the major axis of the spacecraft's orbit drifted 360 degrees in longitude which means

that the data base includes both inbound and outbound passes covering all local times.

For recording occurrences, the plasmasphere was divided into twelve 2 hour local time sectors and the frequency spectrum was divided into two bands with periods of 10-45 seconds and 45-150 seconds, respectively. The quantities recorded are the total number of minutes with data within a local time sector, and the number of minutes containing pulsations in each of the period bands. The recording of pulsations also includes a classification into two different groups according to intensity (amplitude <0.3 mV/m and >0.3 mV/m peak to peak, respectively).

Because electric field measurements in the middle latitude regions of the outer magnetosphere are often dominated by a strong solar oriented sheath field associated with the spacecraft (Heppner et al. (1978b)), this survey is strongly weighted towards data obtained inside the plasmapause. However, a lesser amount of data taken just outside the plasmapause have also been analyzed when valid.

Occurrence Statistics

The data base consists of 4.3×10^3 minutes of data obtained inside the plasmapause. The distribution of these data is shown versus local time in Figure 7. The dashed circle indicates an even distribution. As shown, there is a lack of data around local midnight mainly because of data gaps during time of eclipse of the satellite by the Earth.

Period 10-45 seconds

The percentage of time that pulsations with periods in the range 10-45 seconds were present is shown in Figure 8. These Pc3 pulsations are, as shown, primarily a local day phenomenon with a relative occurrence as high

as 72 percent in the morning sector. The darker shaded area in Figure 8 illustrates the distribution after the weaker of the two intensity groups (amplitude ≲.3 mV/m peak to peak) has been subtracted. The main effect of this subtraction is a further reduction in the relative occurrence on the night side and a movement of the morning maximum towards noon.

Period 45-150 Seconds

The relative occurrence of waves with periods in the range 45-150 seconds is shown in Figure 9. This distribution shows a concentration on the night side with a maximum occurrence just before midnight. In addition, the percentage of time when these pulsations are present, is much lower than for the Pc3 events. In as much as the threshold for detecting these longer period pulsations by visual scanning is slightly higher than for the Pc3's, it is probably more appropriate to compare these percentages of occurrence with those which appeared after subtraction of the weakest Pc3 events in Figure 8.

Occurrence Outside the Plasmapause

The results of the data from outside the plasmapause show the same enhanced occurrence on the dayside for the Pc3 events, but the maximum is closer to noon and the percentages of occurrence are lower than for inside the plasmapause. The longer period pulsations also maintained the maximum on the nightside, but in this case the occurrence percentages are higher than inside the plasmapause. For these pulsations we also have an increased occurrence on the dayside outside the plasmapause.

Dependence of the Kp-index

The large volume of data (Figure 7) and the high occurrence percentages for Pc3 on the dayside should have statistical significance for examining occurrence percentages as a function of the 3 hour Kp index. This has been

done with the result that there does not appear to be a strong correlation. However, there is a slight enhancement in the occurrence percentages with increasing Kp. In the case of the longer period pulsations on the nightside, the limited amount of data and the lower percentage of occurrence make the statistics poor. However, with these limited statistics it appears that most of these pulsations occur during disturbed magnetic conditions.

Polarization

For a number of fairly large amplitude Pc3 events occurring on the dayside at different local times, the polarization has been studied in some detail. The results are given in Table 2.

The ellipticity is defined as the ratio of the minor to the major axis of the polarization ellipse, such that +1 corresponds to right hand (RH) circular polarization, zero to linear, and -1 to left hand (LH) circular. It should be remembered that no measurements of the electric field are made along the Z axis in the solar ecliptic coordinate system, which tends to reduce the magnitude of the radial component at high geomagnetic latitudes. The azimuth angle in Table 2 is the angle between the Earth-centered eastward azimuthal direction and the major axis.

The ellipticity shows that the strongest Pc3 events occurring near or inside the plasmapause are close to being linearly polarized. Based on the azimuth angle, referenced to the eastward direction, these events seem to group into two classes. One class has its azimuth angle close to 0° or 180° (azimuthal) and the other close to 90° (radial). It also appears that the radial group is most often LH polarized and occurs in the morning sector and the azimuthal group is most often RH polarized and occurs in the afternoon.

Discussion

The local dayside maximum in occurrence for the Pc3 events is quite striking, and closely resembles the diurnal distribution of occurrence found at the earth surface and in space (e.g., Jacobs and Sinno (1960), Saito (1964), Heppner et al. (1970), Arthur and McPherron (1975, 1977) and Arthur et al. (1977)) based on the magnetic field component. The maximum percentage of occurrence appears inside the plasmapause, and is in our case higher than 70 in the prenoon sector (Figure 8). Heppner et al. (1970) report a maximum occurrence for Pc3 of 64 percent for $5<L<8$ and 38 percent for $L<5$ based on the magnetic field data from Ogo 3 and 5, while Saito (1964) gives figures for the maximum occurrence of Pc2 and Pc3 at Onagawa, Japan ($L=1.3$), from 60 to 80 percent. However, because the definition of an occurrence depends strongly on the detection threshold these percentages can only be qualitatively compared.

In contrast to Heppner et al. (1970) and Jacobs and Sinno (1960) we have found the maximum percentage of occurrence inside the plasmapause. This probably results from the fact that our reduced data base outside the plasmapause gives a poorer statistic for this region. As discussed later, it has been suggested that a resonant amplification is involved in the generation mechanism for these pulsations. The fundamental period for such a resonant oscillation is given approximately by (Nishida, 1978):

$$T = 2 \int \frac{ds}{\upsilon_A}, \qquad (1)$$

where the integration is to be carried out along a given field line between the conjugate ionospheres. Since the Alfvén speed υ_A has a maximum in the plasmatrough the region where the resonance will most likely be found in Pc3 period range (10-45 s) should be split into two regions situated, respectively, inside the plasmapause and in the outer radiation belt of

magnetosphere (Kopytenko et al. (1975)). We assume that our limited amount of reliable data outside the plasmapause mainly covers the space between these two regions while Heppner et al.'s observations cover the outer as well as the inner region.

If we consider these pulsations as hydrodynamic waves with a phase velocity υ_{ph} equal to the Alfvèn speed υ_A we can express the relationship between the electric E_1 and magnetic B_1 field component as:

$$\frac{E_1}{B_1} = \upsilon_{ph} = \upsilon_A, \tag{2}$$

where it is expected that the oscillation in E_1 and B_1 can be expressed in terms of $\exp[i(\vec{k}\cdot\vec{r}-\omega t)]$, where $\vec{k}$ is the wave vector and ω is the angular frequency. In the equatorial region inside the plasmapause near L=3.5 a typical value for the Alfvèn speed is 750 km/sec. For a fairly large amplitude magnetic pulsation of 2 nT peak to peak, this relation gives an expected value for the electric field component of 1.5 mV/m peak to peak, which is approximately the value we observe for a fairly strong event (e.g., Figure 3, upper panel).

Theoretical models by Southwood (1974, 1975) and Chen and Hasagawa (1974) propose that surface waves in the Pc3 range are exited more or less continuously by a Kelvin-Helmholz instability at the magnetopause over most of the dayside region. These waves propagate inwards where they may couple with a transverse mode resonance of the local magnetic field line when meeting the condition expressed in equation (1). In accordance with this model we observed a heavy concentration of Pc3 pulsations on the dayside. The properties of the shear Alfvèn waves that should be observable at or near the resonant field line are radial orientation in E_1 (azimuthal in B_1) and

linear polarization. Away from the resonant field line, elliptical waves (LH in the morning, RH in the afternoon) with azimuthal orientation should be observed. The most powerful events observed in this study are very close to being linearly polarized, which should indicate that the satellite was moving close to the resonant field line. However, less than half of the events studied so far show the expected radial orientation (see Table 2). The XY-plane of the solar ecliptic coordinate system, in which these measurements are made is, however, not the most suitable for such studies, as an increasing amount of the radial component of the wave is lost when the satellite is moving away from the equatorial plane. Arthur et al. (1977) also reported both radial and azimuthal pulsations with nearly linear polarization. Although linearly polarized they interpreted the radial class of events (which correspond to the azimuthal class for the electric field) as observations away from the field line. In the events studied in detail, we primarily find LH polarizations in the morning sector and RH polarizations in the afternoon sector as predicted by the theoretical model. The tendency for more radial cases prenoon and more azimuthal cases postnoon can not, however, be explained in light of the existing model for Pc3. The number of events investigated is, however, limited.

Pulsations observed in the frequency range 45-150 seconds were in general composed of many frequency components, that were normally not harmonically related. Pi1 waves were often seen as high frequency riders on these pulsations. This complex frequency spectrum, and the fact that these pulsations are concentrated on the nightside with a maximum occurrence frequency in the two hour sector just before local midnight, strongly support our suggestion that these pulsations should be classified as Pi 2 rather

Pc 4 (Rostoker (1967), Doobov and Mainstone (1973a), Smith (1973)). Based on data from Explorer 45 near L=5, Lin and Cahill (1975) report observations of Pi 2 periods from 40 to 200 s with 80 s (12.5 mHz) as the most dominant period. In agreement with these results we observed Pi 2 events at all frequencies within the Pi 2 band, with the dominant frequency usually between 10-16 mHz.

Doobov and Mainstone (1973b) proposed that there are six possible cavities between the different boundaries on the magnetospheric nightside where resonance conditions may exist for hydrodynamic waves (see their Figure 2). Pi 2 oscillations are generally considered to be the result of the impact of a stream of energetic particles on the closed field lines in the nightside magnetosphere (e.g., Doobov and Mainstone (1973b). Lin and Cahill (1975) suggest that cavities with closed magnetosphere boundaries provide the best candidates for explaining Pi 2. According to Doobov and Mainstone (1973b) this typically corresponds to periods of 44, 77 and 87 s. It is interesting to note that two of these three candidates (77 and 87 s) are located in the center of the band where we most frequently observe the dominant period of the Pi 2 events.

In contrast to previous ground based work (Rostoker (1967), Smith (1973)), our result indicates that Pi 2 are more likely to occur under magnetically disturbed conditions. However, the low number of Pi 2 event does not give an adequate statistic for drawing solid conclusions.

Summary and Conclusions

The characteristics of Pc 3 pulsations determined or confirmed from these electric field observations can be summarized as follows:

1. Coherent pulsations in the electric field are very common on the local dayside near and inside the plasmapause.

2. They occur at all frequencies in the Pc 3 band, but the most common occurrence is between 30 and 50 mHz.

3. The observed amplitude ranges from less than 0.1 mV/m to 4-5 mV/m peak to peak.

4. The strongest events are usually nearly linearly polarized. The direction of rotation for the electric field vector is most often LH in the morning sector and RH in the afternoon sector.

5. Based on azimuth angle, there are two distinct classes of Pc 3; nearly radial and nearly azimuthal. There is a tendency for more radial cases prenoon and more azimuthal cases postnoon.

Similarly, the main characteristics found for Pi 2 can briefly be summarized as follows:

1. Pi 2 pulsations, which do not occur as frequently as those in Pc 3 band, are mainly concentrated on the nightside and have their maximum percentage of occurrence outside the plasmapause.

2. These pulsation events are usually composed of several frequency components, with the dominant frequency most often in the band 10 to 16 mHz. Pi 1 pulsations are often observed as high frequency riders on the Pi 2 pulsations.

3. Pi 2 pulsations occur typically with an amplitude near 2 mV/m peak to peak, but events with amplitudes as high as 20 mV/m peak to peak have been observed.

The above summarized characteristics of events in the Pc 3 range are consistent with statistics based on observations of the magnetic field of waves from a synchronous orbit by Arthur et al., (1977). The overall picture

described is also consistent with the model of a local field line resonance excited by a plasmawave originating at the magnetopause as proposed by Southwood (1974, 1975) and Chen and Hasagawa (1974). The amplitude of the electric field is also consistent with what we would expect from knowledge of the magnetic field component of the wave and the Alfvén speed.

The concentration of Pi2 events on the nightside is consistent with previous observations. The dominant Pi2 frequencies we observe are also consistent with the predictions of Doobov and Mainstone (1973b) which are based on having a stream of energetic particles impact on the closed field lines in the nightside magnetosphere.

In the one year of data examined, pulsations in the Pc1 range appear on only one inbound pass, which makes Pc1 a rather rare phenomenon at low and moderate latitudes in the plasmasphere.

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TABLE 1: Parameters of the ISEE-1 Spacecraft, and its Initial Orbit. (After Ogilvie et al., (1977))

Spin rate, rev/min	19.7
Spin axis alignment	Perpendicular to the ecliptic plane
Perigee distance from earth center, R_E	1.044
Apogee distance from earth center, R_E	23.17
Eccentricity	.913787
Inclination (equator), degrees	28.766

TABLE 2: CHARACTERISTICS OF SELECTED STRONG PC-3 MICROPULSATION EVENTS

Date	Time UT	Time LT	L-Value	Geomagn. Lat. Deg.	Max Ampl. mV/m p.t.p.	Period S	Azimuth* Deg.	Ellipticity*
2/28/78	1543	0620	3.3	-15	1.0	24	90	-.5
3/7/78	2003	0640	3.4	-33	2.5	24	90	-.2
1/30/78	2312	0820	4.0	-27	2.0	17	90	-.3
9/3/78	0324	1000	5.2	31	1.4	21	160	-.1
1/9/78	1100	1005	3.1	-11	.8	25	100	+.2
8/10/78	0546	1110	4.9	31	1.7	29	20	-.1
12/11/77	1839	1145	3.2	- 5	1.5	40	80	+.5
12/2/77	1205	1210	3.9	-23	1.2	25	90	+.1
11/15/77	1131	1300	3.7	- 9	3.2	45	165	+.4
6/4/78	0756	1500	4.6	28	1.4	21	25	-.1
10/1/78	1730	1530	4.7	-21	3.0	36	180	+.3
6/1/78	2246	1545	8.2	49	5.0	40	0	+.1
9/7/78	1945	1700	4.8	-17	0.6	24	135	-.1
4/24/78	1652	1740	4.4	39	10.0[x]	20	15	+.2
9/3/78	0120	1800	3.9	-24	0.3	16	140	+.2

* - 0 or 180 deg: azimuthal orientation
90 deg: radial orientation

\+ - Minus sign: Left hand polarization
Plus sign: Right hand polarization

x - The event studied on April 24, 1978 is a large amplitude impulsive event lasting only for a few cycles.

FIGURE CAPTIONS

Figure 1. Projection of the ISEE-1 orbit into the equatorial plane. The inserted sketch shows the antenna configuration with the rotation direction in the spin plane.

Figure 2. Three samples of spin modulated raw data from the double probe electric field instrument on ISEE-1. The arrows indicate the time when the reference probe is pointing at the sun. Superimposed on the spin modulation, a short period (Pc1) wave can be seen.

Figure 3. Three examples of pulsations in the Pc3 period range. The solid curves give the amplitude (scale on the left hand axis) and the dotted curves give the phase angle (scale on the right axis) for the observed electric field which includes the induced $\vec{v} \times \vec{B}$ term.

Figure 4. Spectral density of parts of the pulsation events shown in Figure 3. Solid line gives the result from a maximum entropy method while the dashed line gives the result from calculations based on the method described by Blackman and Tukey (1958).

Figure 5. Three examples of pulsations in the period range 45-150 seconds. (Axes as in Figure 3).

Figure 6. Spectral density of parts of the pulsation events in Figure 5

Figure 7. Distribution of data versus local time inside the plasmapause. The dashed circle indicate an even distribution.

Figure 8. Percentage of time that pulsations in the period range 10-45 seconds were present inside the plasmapause, versus local time. The darkest hatching gives the distribution when the weaker pulsations are subtracted out.

Figure 9. Percentage of time that pulsations in the period range 45-150 seconds were present inside the plasmapause, versus local time.

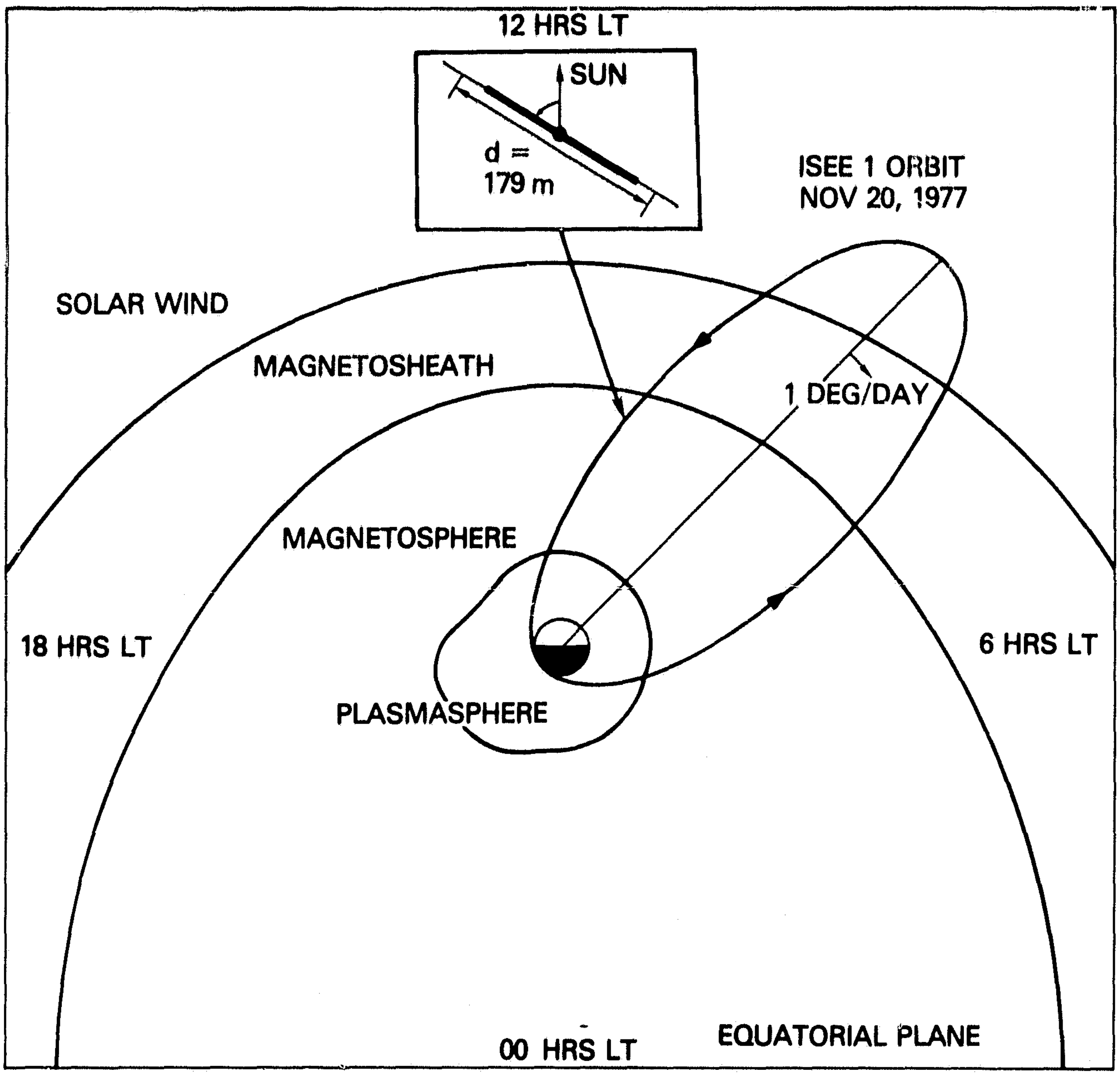

12 HRS LT
SUN
d =
179 m
ISEE 1 ORBIT
NOV 20, 1977
SOLAR WIND
MAGNETOSHEATH
1 DEG/DAY
MAGNETOSPHERE
18 HRS LT
6 HRS LT
PLASMASPHERE
00 HRS LT
EQUATORIAL PLANE

FIGURE 1

ISEE 1 ELECTRIC FIELD DATA

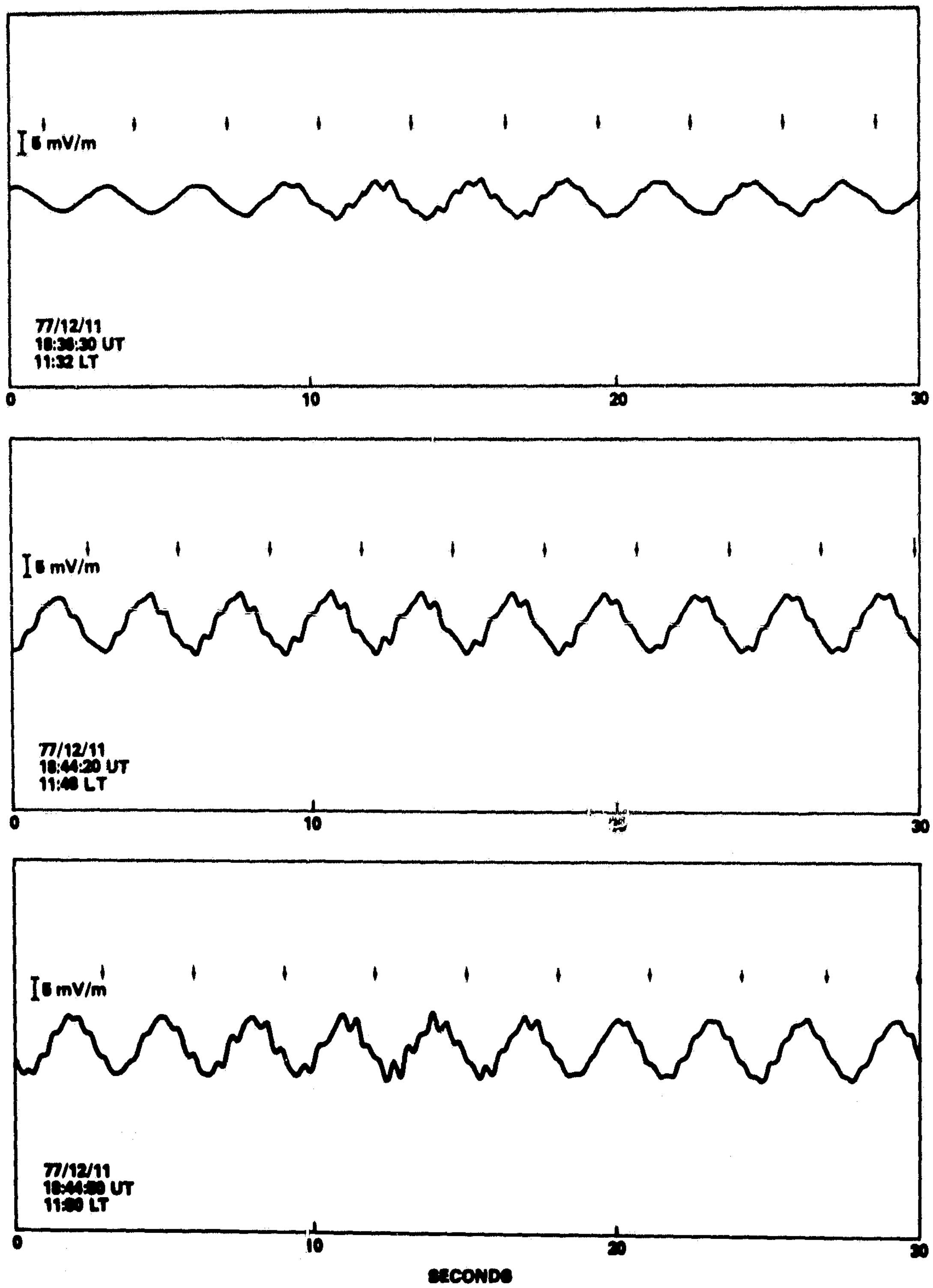
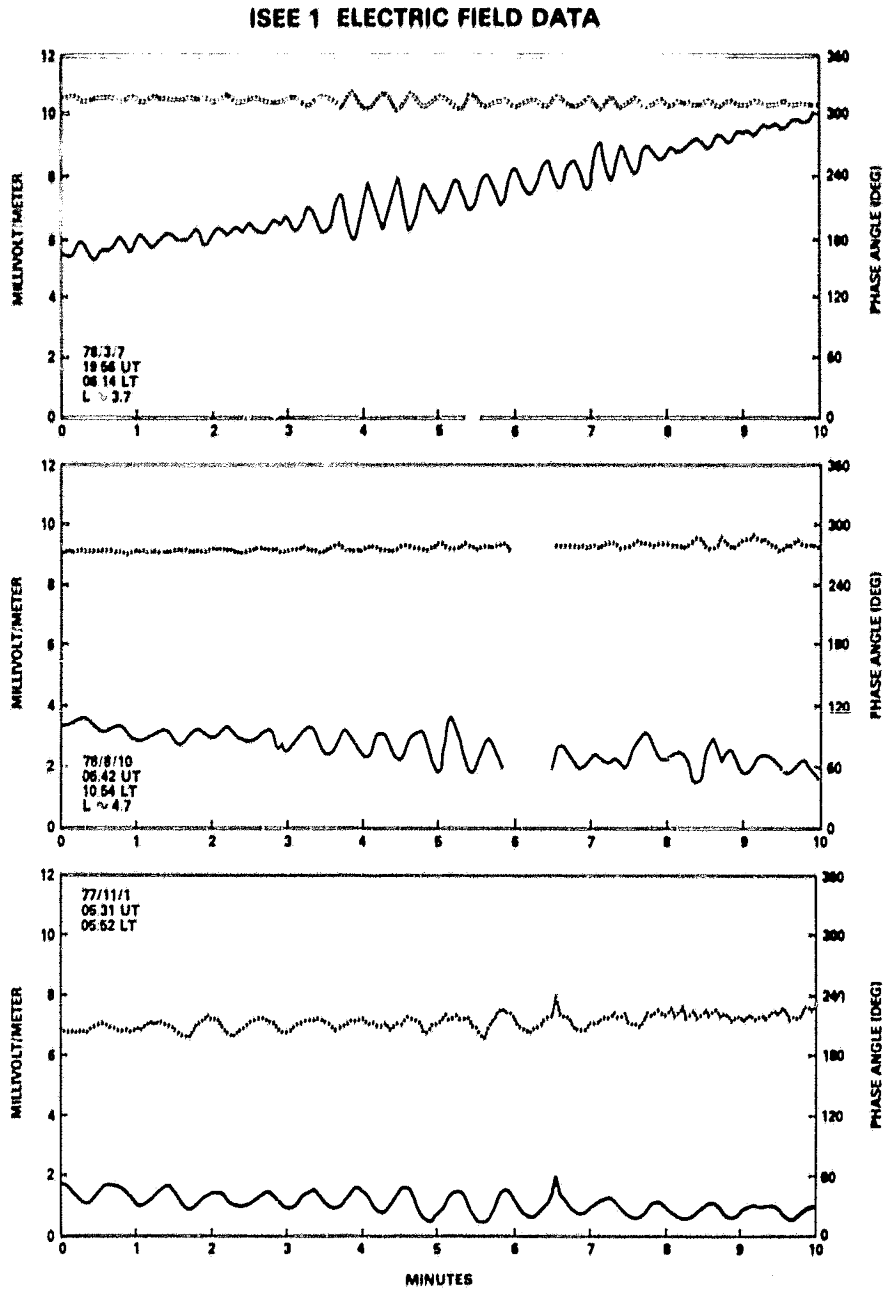


FIGURE 2



ISEE 1 ELECTRIC FIELD DATA
MILLIVOLT/METER
PHASE ANGLE (DEG)
78/3/7
19 56 UT
06 14 LT
L ~ 3.7
78/8/10
06.42 UT
10.54 LT
L ~ 4.7
77/11/1
06 31 UT
05 52 LT
MINUTES

FIGURE 3

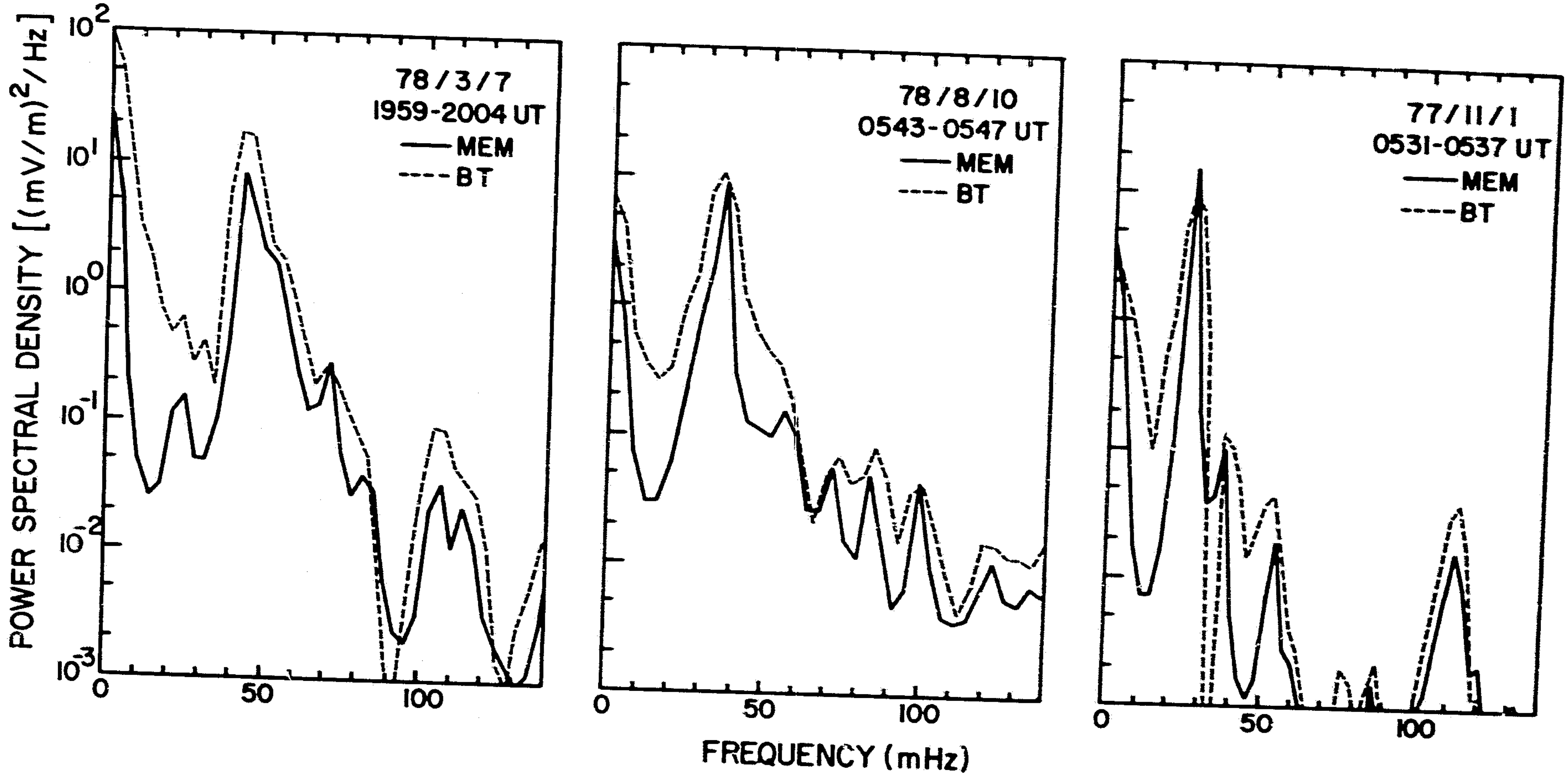

POWER SPECTRAL DENSITY [(mV/m)²/Hz]
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
78 / 3 / 7
1959-2004 UT
MEM
BT
78 / 8 / 10
0543-0547 UT
MEM
BT
77 / 11 / 1
0531-0537 UT
MEM
BT
0
50
100
FREQUENCY (mHz)

FIGURE 4

ISEE 1 ELECTRIC FIELD DATA

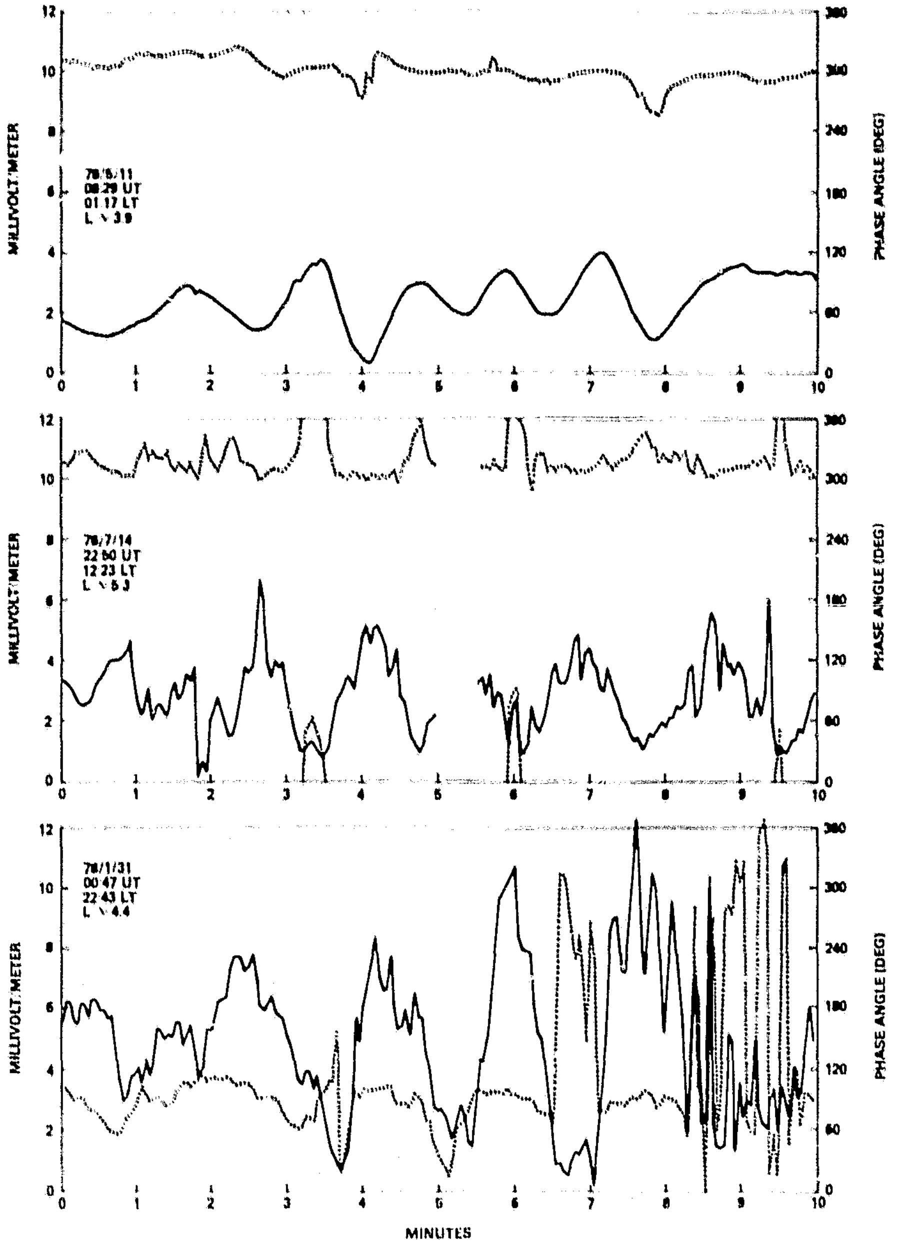
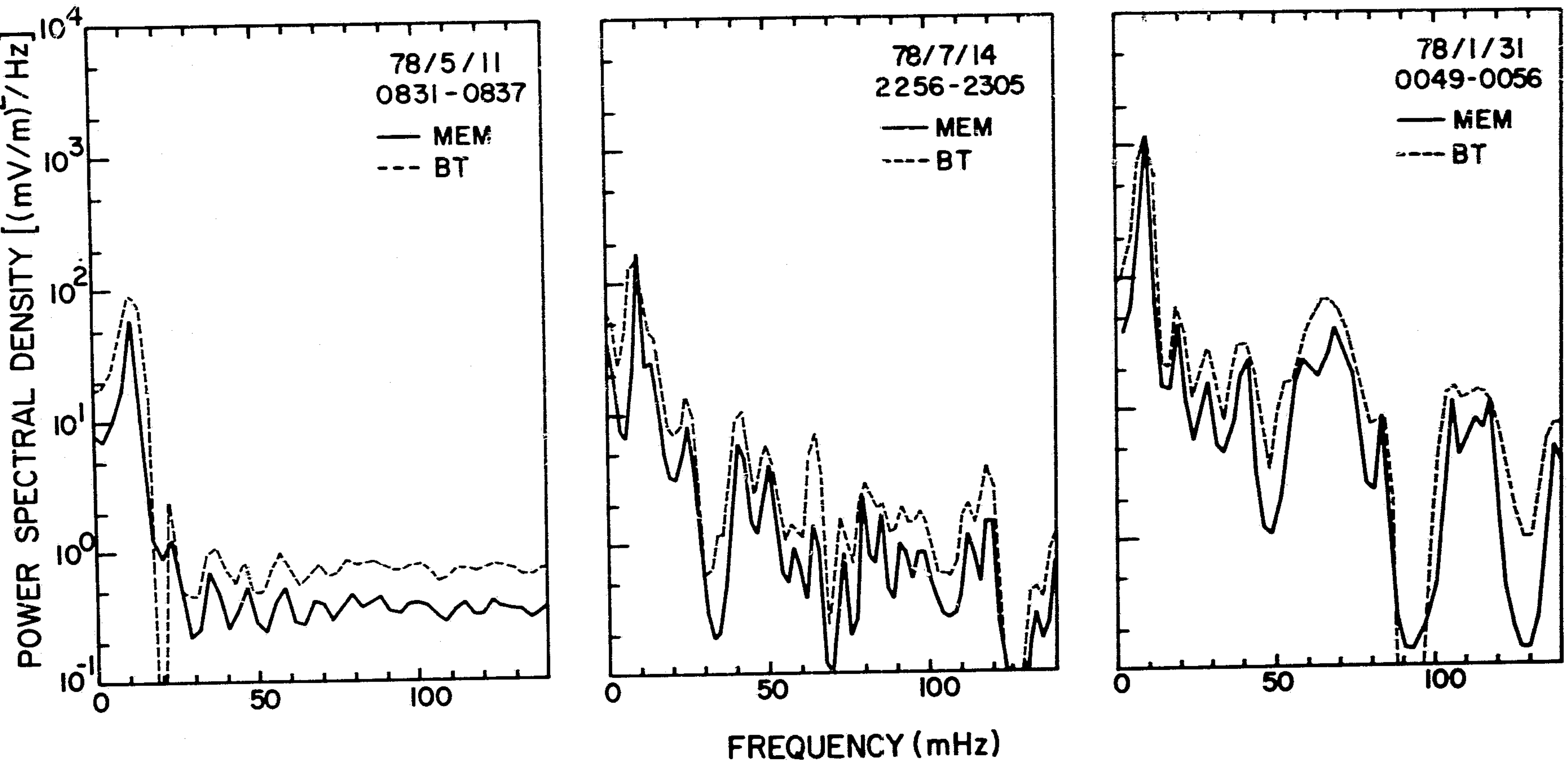
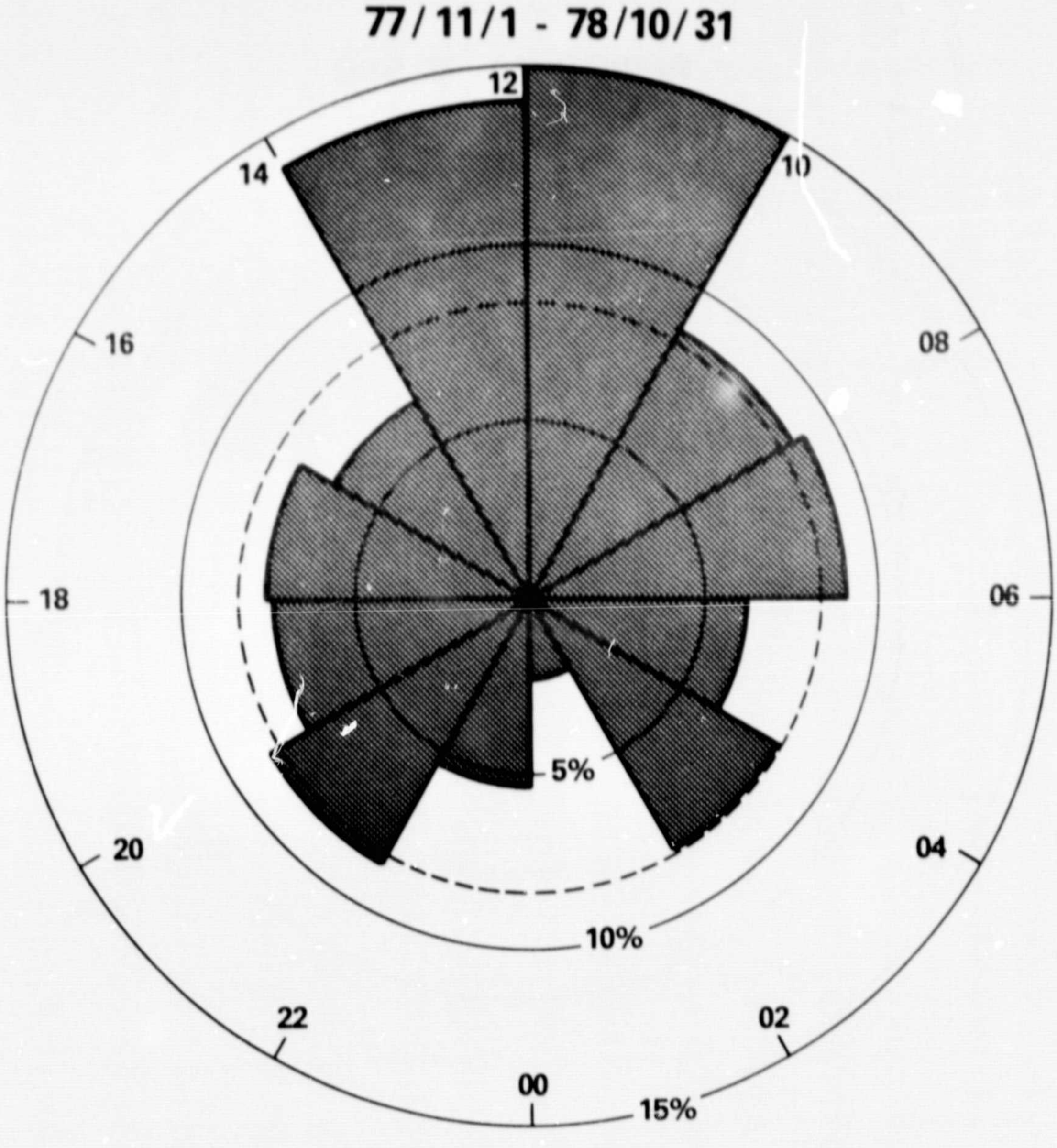


FIGURE 5



POWER SPECTRAL DENSITY [(mV/m)²/Hz]
10⁴
10³
10²
10¹
10⁰
10⁻¹
78/5/11
0831-0837
MEM
BT
78/7/14
2256-2305
MEM
BT
78/1/31
0049-0056
MEM
BT
0
50
100
FREQUENCY (mHz)

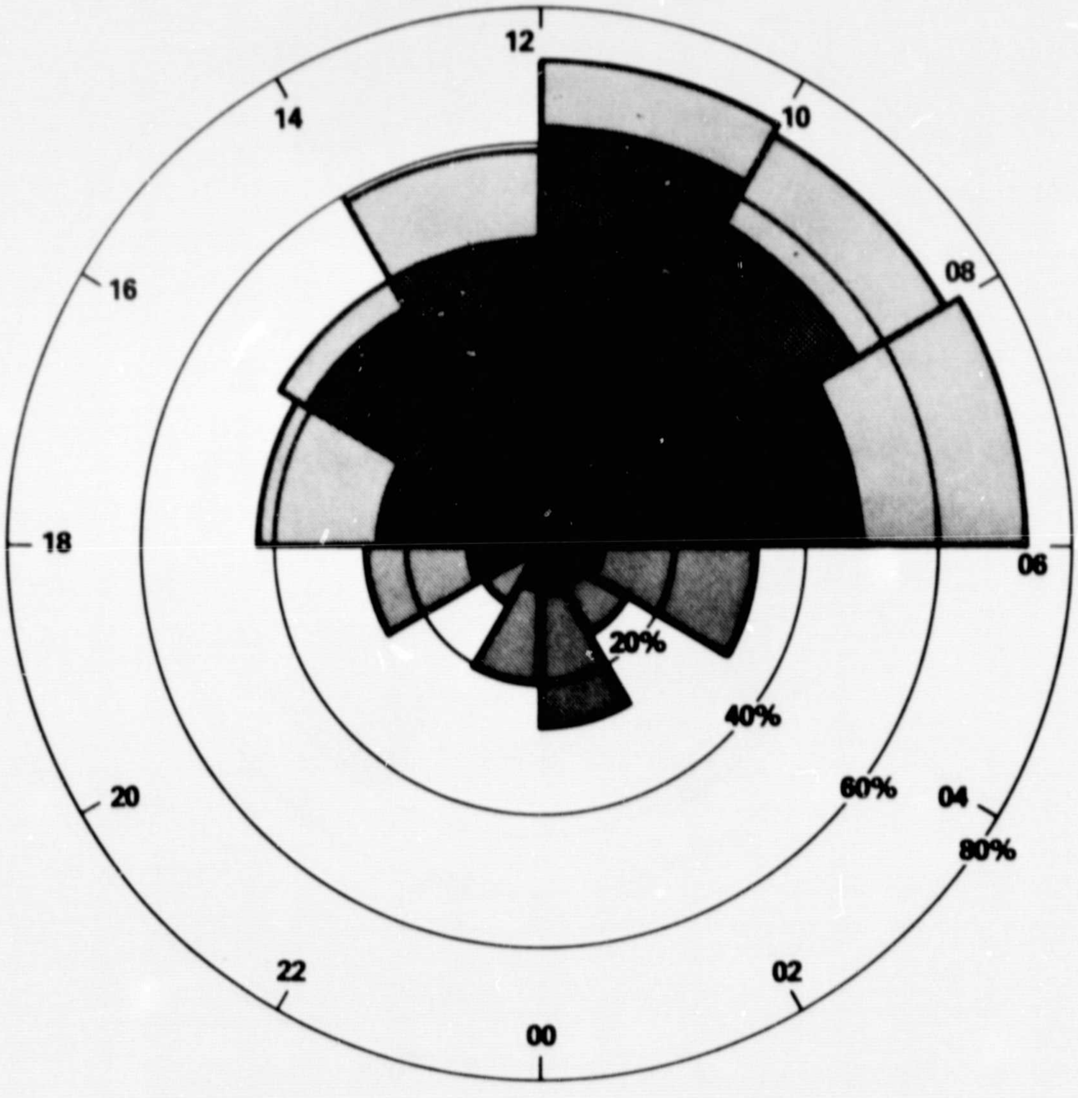
FIGURE 6



DISTRIBUTION OF DATA INSIDE THE PLASMAPAUSE
TOTAL: 73 HRS

FIGURE 7

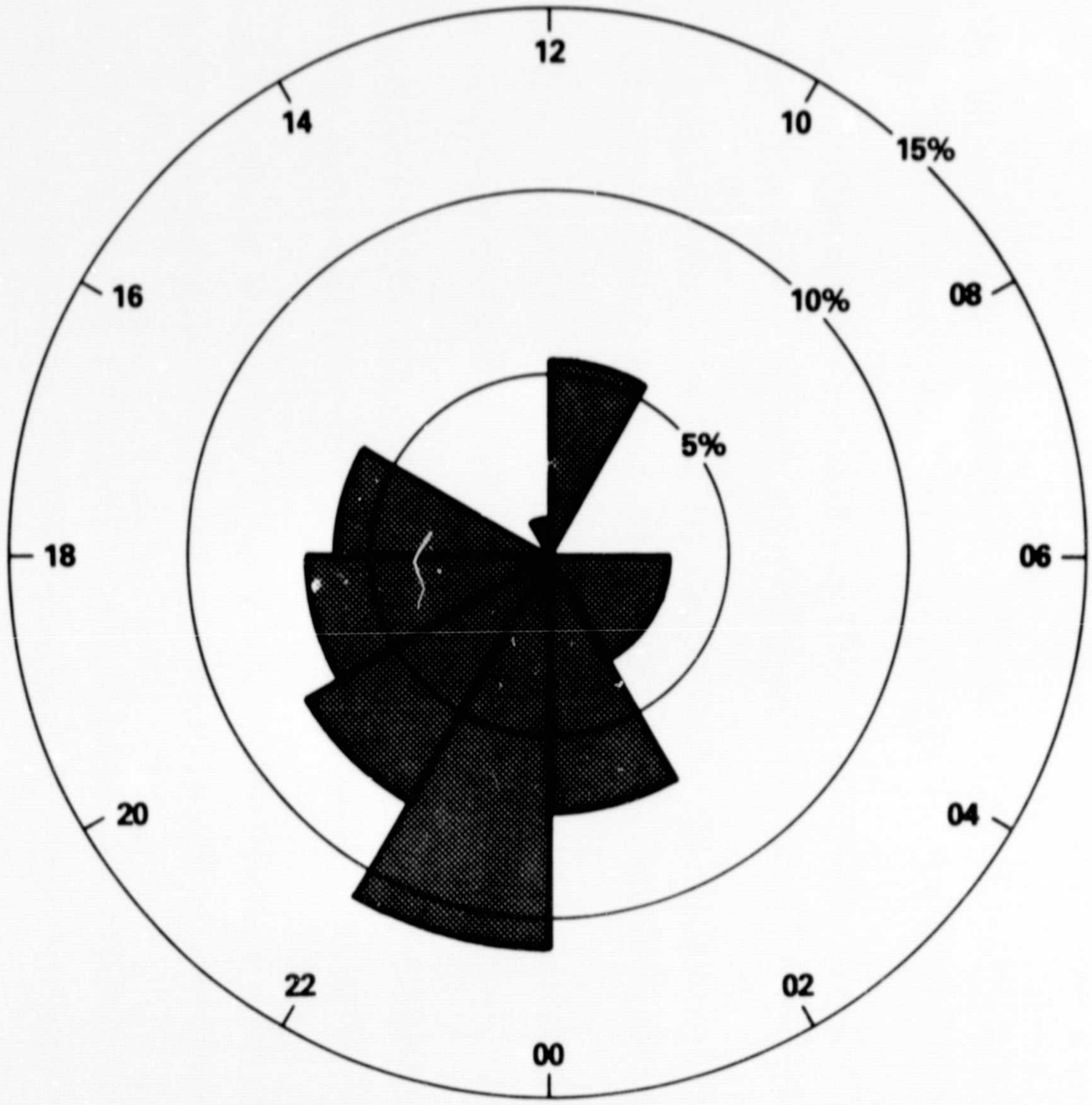
PERIOD 10 - 45 SEC



PERCENTAGE OF TIME THAT PULSATIONS WERE PRESENT

FIGURE 8

PERIOD 45 - 150 SEC



PERCENTAGE OF TIME THAT PULSATIONS WERE PRESENT

FIGURE 9